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# 1.01-Pb/s (12 SDM/222 WDM/456 Gb/s) Crosstalk-managed Transmission with 91.4-b/s/Hz Aggregate Spectral Efficiency

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**Abstract** We demonstrate 1.01-Pb/s transmission over 52 km with the highest aggregate spectral efficiency of 91.4 b/s/Hz by using low-crosstalk one-ring-structured 12-core fiber. Our multi-core fiber and compact fan-in/fan-out devices are designed to support high-order modulation formats up to 32-QAM in SDM transmission.

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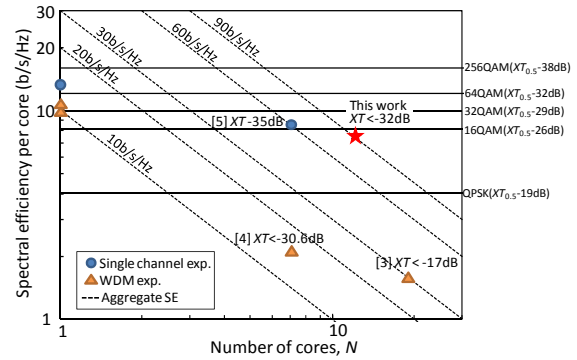
## Introduction

Space division multiplexing (SDM) is a promising approach to increasing the transmission capacity of fiber<sup>1-6</sup>. SDM experiments on multi-core fibers (MCFs) have demonstrated large capacity transmission, up to 305-Tb/s<sup>3</sup>.

In order to increase MCF transmission capacity, increasing the aggregate spectral efficiency (SE), defined as a product of the number of cores  $N$  and the SE per core, is necessary. Figure 1 plots  $N$  and SE per core of recent transmission experiments<sup>3-5</sup>. Contour plots of aggregate SE (dashed lines), and the required crosstalk for 0.5 dB penalty with several multi-level modulation formats ( $XT_{0.5}$ ) are also shown in Fig.1. Crosstalk management to design the optimum combination of  $N$  and SE per core for maximum aggregate SEs is then essential. The crosstalk from the other cores generally increases with the number of cores while the crosstalk tolerance decreases with higher order multi-level signal transmission<sup>2,7,8</sup>. For 19 core fiber, the highest  $N$  and aggregate SE of 30 b/s/Hz with QPSK modulation has been reported<sup>3</sup>. However, it seems difficult to employ higher order multi-level signals due to the excessive crosstalk. For seven core fibers, the crosstalk,  $XT$ , of less than -30 dB has been realized, and QPSK WDM transmission with 15-b/s/Hz aggregate SE and 32-QAM-OFDM single channel transmission with 60-b/s/Hz aggregate SE have been reported<sup>4,5</sup>.

In this paper, we optimize the combination of the number of cores and multiple level of QAM by taking into account of the crosstalk among SDM channels. By employing the 32QAM format and the low crosstalk of newly-developed 12 core fiber with one ring structure and fan-in/out devices (FI/FOs), we demonstrate 1.01-Pb/s WDM transmission, record capacity per single

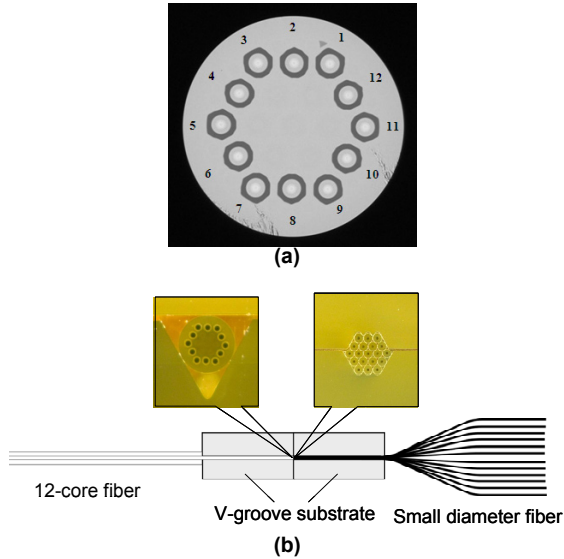
strand fiber, and confirm the feasibility of MCF transmission with the highest aggregate SE of 91.4 b/s/Hz.



**Fig.1:** Aggregate spectral efficiency of MCF transmission as a function of the number of cores and spectral efficiency per core.

## 12-core fiber and fan-in/fan-out device

Figure 2 shows the schematic configuration of the 12-core MCF and fan-in/fan-out device (FI/FO). We propose an MCF whose cores are arranged on one ring so that the crosstalk is small even if the number of cores is larger than seven. The MCF has a core pitch of 37  $\mu\text{m}$  and a cladding diameter of 225  $\mu\text{m}$ . The effective core area ( $A_{\text{eff}}$ ) at 1550 nm and 1625 nm are 80.7  $\mu\text{m}^2$  and 84.7  $\mu\text{m}^2$  on average, respectively. Attenuation at 1550 nm and 1625 nm are 0.199 dB/km and 0.207 dB/km, respectively. Dispersion at 1550 nm and 1625 nm are 19.3 ps/nm/km and 24.0 ps/nm/km, respectively. The FI/FO splits the MCF's twelve cores into twelve individual small diameter fibers. The core pitch and cladding diameter of the FI/FO are 37  $\mu\text{m}$  and 225  $\mu\text{m}$ , respectively. In the FI/FO, the MCF and small diameter fibers are connected via a V-groove substrate. 52-km MCF and the FI/FO are connected by fusion-splicing. The mode field diameter of the small diameter fibers of FI/FO is 10.6  $\mu\text{m}$ , and  $A_{\text{eff}}$  is 88  $\mu\text{m}^2$ . The average

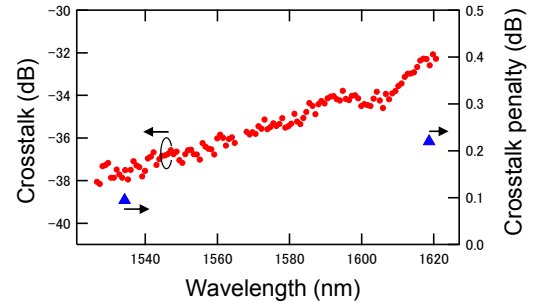


**Fig. 2:** Schematic configuration of one-ring structured 12-core fiber (a) and FI/FO (b).

measured crosstalk of the FI from core1 to core2 was -57 dB at 1550 nm. The total crosstalk from all other cores of the FI and the FO after 52-km MCF propagation is shown in Fig.3. The average total crosstalk at 1526-1620 nm ranged from -38 to -32 dB. The losses of FI and FO including the fusion splice losses were 0.7–2.9 dB and 0.7–2.0 dB, respectively. The total losses between the FI input and the FO output port including the MCF 52 km-propagation ranged from 12.4 to 14.8 dB.

### Experimental setup

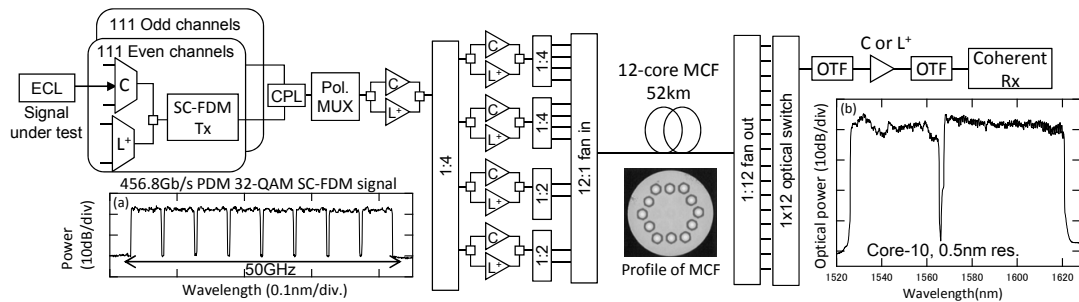
Figure 4 shows the experimental setup. In this experiment, we generated 222-channel WDM signals of 456-Gb/s PDM-32QAM single-carrier frequency-division-multiplexing (SC-FDM) signals; transmitter and receiver setups were based on previous reports<sup>9,10</sup>. 222 CW optical carriers (1526.44-1565.09 nm, and 1567.95-1620.06 nm) with 50-GHz spacing in the C- and extended L- (L<sup>+</sup>) bands were used in the transmitter. Each carrier was modulated to create a 12.5-GHz spaced 4-subcarrier signal, and each subcarrier was simultaneously modulated by an IQ-modulator driven by an



**Fig. 3:** Wavelength dependency of crosstalk of MCF with FI/FO.

electrical 5.71-Gbaud Nyquist-pulse-shaped 32QAM signal. The 4-subcarrier signal was split in two, one of them was delayed and frequency-shifted by 6.25 GHz, and recoupled to form a 6.25-GHz-spaced 8-subcarrier SC-FDM signal. The even and odd SC-FDM signals then were combined with an optical coupler, and polarization multiplexed with 25-nsec delay. Consequently, each 50-GHz spaced channel consisted of eight PDM-32QAM subcarriers with line rate of 456 Gb/s (net data rate: 380Gb/s), resulting in the SE of 7.6 b/s/Hz assuming 20% FEC overhead. Its spectra are shown in the inset of Fig.4. C- and L<sup>+</sup>-band EDFAs<sup>11</sup> with parallel configuration were used to compensate the loss of the modulation sections. In this experiment, we used a tunable external-cavity laser (ECL) with a linewidth of about 60 kHz for the test channel; the remaining lasers were DFB lasers (linewidth ~2 MHz). The signals were then amplified by C- and L<sup>+</sup>-band EDFAs and separated into 12 SDM channels by 1x4 couplers and 1x2 couplers.

The transmission line consisted of a 52-km 12-core MCF. Twelve SDM channels were generated by delaying copies of the original WDM channels, and each SDM channel was fed into the corresponding core by 12:1 fan-in device. The average power of the 222WDM channels was set to -4dBm/ch considering nonlinear impairment. The highest aggregate SE of 91.4 b/s/Hz was achieved. After transmission,



**Fig. 4:** Experimental setup (a) Optical spectra of single channel 456.8 Gb/s PDM 32-QAM SC-FDM signal (left) (b) Received Optical spectrum after 52km transmission (core-10) (right).

the SDM channels (signals via corresponding cores) were de-multiplexed by the fan-out device. Desired channel was selected by optical switch and fed into the coherent receiver.

At the receiver side, the received signals were filtered by optical tunable filters (OTFs), and detected by a polarization-diversity intradyne receiver. We used a free-running ECL with a linewidth of  $\sim 70$  kHz as the LO. Real and imaginary parts of the two polarization tributaries were detected and digitized by the coherent receiver. In this experiment, four subcarriers were simultaneously received, and subcarrier separation and demodulation were post-processed offline using the algorithm described in a previous report<sup>9,10</sup>. Bit error ratio (BER) was calculated from the 1Mbit demodulated signals.

### Experimental results

Figure 5 shows the back-to-back OSNR-penalty characteristics due to crosstalk at the wavelength of 1545.32 nm. The penalty at the worst crosstalk of the transmission experiment, -32 dB, was 0.3 dB, which is close to the theoretical value of 32-QAM.

Next, we discuss the performance of 222-channel WDM transmission. Thanks to the low crosstalk MCF and FI/FO devices, the crosstalk from all other SDM channels was -32 dB under the signals. We also measured the Q-factor penalty of core2 due to the crosstalk components, shown as the triangles in Fig. 3. The Q-factor penalty of core2 after 52-km transmission was within 0.22 dB. The measured Q-factor performance after 52-km MCF transmission is shown in Fig.6. Each plot represents the Q-factor calculated from the average BER of the 8 subcarriers. Q-factors of all 222 channels for twelve cores were confirmed to be better than 6.90 dB, which

exceeds the Q-limit (6.75 dB, dashed line) of continuously interleaved BCH hard decision FEC techniques with 20% overhead.

### Conclusions

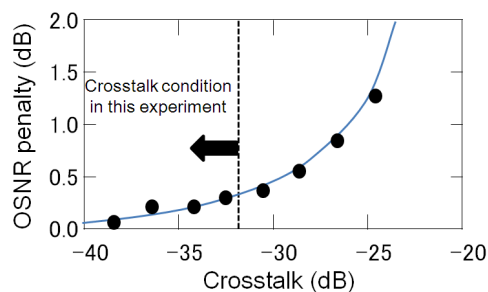
In order to realize high capacity MCF transmission, we optimized the combination of the number of cores and multiple level of QAM by taking account of the crosstalk between SDM channels. We successfully demonstrated the 52-km 12-core fiber transmission of 222 WDM channels, 456-Gb/s signals, by employing PDM-32QAM format and low crosstalk 12 core fiber and fan-in/out devices. These allowed the capacity per fiber to exceed 1.01-Pb/s for the first time with the highest aggregate SE of 91.4 b/s/Hz and confirmed the feasibility of MCF transmission with 400-Gb/s-class high speed channels.

### Acknowledgements

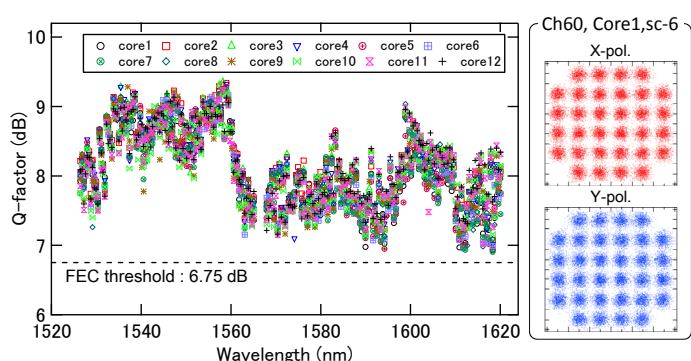
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**Fig. 5:** OSNR-penalty characteristics due to crosstalk under single channel condition.



**Fig. 6:** Measured Q-factors after 52 km transmission.